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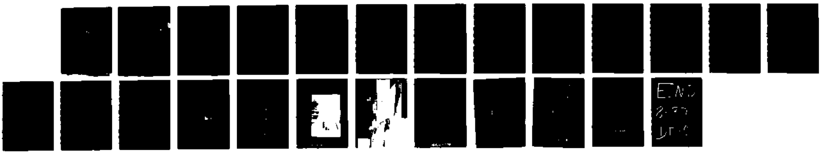

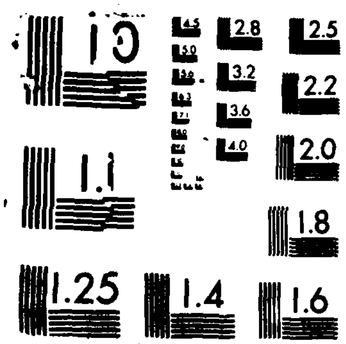
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William W. Willmarth

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The structure of the fluctuating flow field in a turbulent boundary layer has been investigated with the aid of extremely small hot-wire probes. Two investigations were conducted. In one investigation a small X-array hot-wire probe, with dimensions (length and spacing) of the order of 2.5 viscous lengths (100 microns) was constructed and used to measure the small scale structure of the velocity fluctuations and the Reynolds stress near the wall. It was found that very small, intense contributions to the Reynolds stress occur with a scale of the order of the viscous length. In the other investigation a pair of single hot-wires which were of a length of the order of one-half the viscous length (50 microns) were used to demonstrate the existence of shear layers near the wall with an intensity comparable to the mean shear stress at the wall.

We have also measured the wall pressure fluctuations produced on the surface of a long cylinder in a wind tunnel. We found the intensity, spatial scale and frequency content of the pressure fluctuations in a wind tunnel to be significantly different from the pressure

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Abstract (continued)

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One ~~of the~~ primary results of the investigation is ~~that~~ when large scale turbulence is present in the flow upstream of the cylinder, large amplitude, low frequency circumferentially averaged pressure fluctuations are produced on the cylinder surface. The circumferentially averaged pressure fluctuations are caused by pressure fluctuations in the free stream turbulence and by the aerodynamic interaction of cylinder with the free stream turbulence. A three-sensor hot-wire probe was used to measure the three components of the velocity fluctuations in the free stream at a point 3.5 diameters from the axis of the cylinder. When the free stream turbulence level was low, the instantaneous average of the pressure fluctuations around the circumference could be estimated from the free stream velocity fluctuations near the measuring point on the cylinder. The correlation coefficient was of the order of 0.6. For relatively large amplitude free stream turbulence the velocity fluctuations at one point in the free stream near the cylinder could not be simply related to the circumferential average of the pressure flucutations on the cylinder surface.

During the last year of the contract, at a reduced funding level, two larger circumferential average pressure transducers were constructed which can be positioned at various distances along the cylinder axis. An attempt was made to measure the space-time correlation of the instantaneous circumferential pressure fluctuations on a cylinder in the atmosphere. This was not successful owing to imperfect vibration isolation of the circumferential pressure transducers.

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AN INVESTIGATION OF FLOW FIELD AND WALL PRESSURE FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS ON PLATES AND CYLINDERS

Submitted by: William W. Willmarth
Department of Aerospace Engineering
University of Michigan, Ann Arbor, MI. 48109

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ABSTRACT

The structure of the fluctuating flow field in a turbulent boundary layer has been investigated with the aid of extremely small hot-wire probes. Two investigations were conducted. In one investigation a small X-array hot-wire probe, with dimensions (length and spacing) of the order of 2.5 viscous lengths (100 microns) was constructed and used to measure the small scale structure of the velocity fluctuations and the Reynolds stress near the wall. It was found that very small. intense contributions to the Reynolds stress occur with a scale of the order of the viscous length. In the other investigation a pair of single hot-wires which were of a length of the order of one-half the viscous length (50 microns) were used to demonstrate the existence of shear layers near the wall with an intensity comparable to the mean shear stress at the wall.

We have also measured the wall pressure fluctuations produced on the surface of a long cylinder in a wind tunnel. We found the intensity, spatial scale and frequency content of the pressure fluctuations in a wind tunnel to be significantly different from the pressure fluctuations observed by other investigators on long cylinders towed in the ocean. The present experimental investigation was designed to study the instantaneous circumferential average of the pressure fluctuations on a cylinder. A new transducer was developed which responds to the instantaneous circumferential average of the pressure on a narrow band around the cylinder. Measurements were made with the transducer in wind tunnels and in the atmosphere.

One of the primary results of the investigation is that when large scale turbulence is present in the flow upstream of the cylinder, large amplitude, low frequency, circumferentially averaged pressure fluctuations are produced on the cylinder surface. The circumferentially averaged pressure fluctuations are caused by pressure fluctuations in the free stream turbulence and by the aerodynamic interaction of cylinder with the free stream turbulence. A three-sensor hot-wire probe was used to measure the three components of the velocity fluctuations in the free stream at a point 3.5 diameters from the axis of the cylinder. When the free stream turbulence level was low, the instantaneous average of the pressure fluctuations around the circumference could be estimated from the free stream velocity fluctuations near the measuring point on the cylinder. The correlation coefficient was of the order of 0.6. For relatively large amplitude free stream turbulence the velocity fluctuations at one point in the free stream near the cylinder could not be simply related to the circumferential average of the pressure fluctuations on the cylinder surface.

During the last year of the contract, at a reduced funding level, two larger circumferential average pressure transducers were constructed which can be positioned at various distances along the cylinder axis. An attempt was made to measure the space-time correlation of the instantaneous circumferential pressure fluctuations on a cylinder in the atmosphere. This was not successful owing to imperfect vibration isolation of the circumferential pressure transducers.

Results of the investigation:

Investigations of small scale turbulent structure:

The experimental investigation began with the study of small scale velocity fluctuations in turbulent boundary layers at relatively high Reynolds numbers using a very small, specially constructed hot-wire probe in the form of an X array and a novel method for acquiring data from the two hot-wires of the probe. Probe calibration data and the data measured by the probe during the experiment were acquired and stored with the aid of a digital computer. The computer was then programed to analyze the stored probe data to determine the instantaneous velocity using a "look-up" table constructed from the calibration data.

It was found that the X array probe was unable to resolve the small scale velocity fluctuations owing to poor spatial resolution in which each wire of the probe X array was exposed to a different velocity. This result is described in the publication **Willmarth and Bogar (1977)**, see the list of papers and reports in **Appendix A.**

In a later investigation a pair of extremely small hot-wires (smaller than the viscous length) were constructed and used to measure the instantaneous velocity gradient in a turbulent boundary layer very near the wall. It was concluded that instantaneous velocity gradients with intensity of the order of the velocity gradient at the wall and scale comparable to the viscous length exist in the boundary layer near the wall at Reynolds numbers of the order of 10^6. Thus, the small scale turbulent structure near the wall cannot be accurately be resolved by conventional hot-wire systems and techniques. The method of constructing such hot-wires and these results are described in the reprint **Willmarth and Sharma (1984)**, (see paper listed in **Appendix A**).

In a further investigation, the measurement of vorticity in a turbulent flow with a Kovasznay type vorticity probe was studied, in collaboration with research workers from the Max-Planck-Institut fur Stromungsforschung in Gottingen, West Germany. It was concluded that the vorticity signal from a conventional, Kovasznay type vorticity probe was contaminated by the streamwise and two transverse velocity components. The streamwise velocity component contamination can be removed using the instantaneous streamwise component information available from the conventional probe. However, the contamination caused by the two transverse components can only be removed if these other components are separately and simultaneously measured. This work is described in the reprint **Kastrinakis, Eckelmann and Willmarth (1979)** listed in **Appendix A.**

Pressure Fluctuations on Cylinders:

This part of the investigation was an investigation of the large amplitude, low frequency and large scale pressure fluctuations observed on the surface of a long cylinder towed through water. At the beginning of the project the P.I. had the good fortune to observe an underwater motion picture of a long cylinder being towed through ocean. The cylinder was clearly not straight nor of uniform diameter. During towing the cylinder was not straight and long portions of it were not parallel to the towing direction. This observation and the fact that the pressure fluctuations on the cylinder must be related to the flow and pressure fluctuations in the environment and to the unavoidable nonuniformity and yawing motion of a long cylinder (which could not possibly be perfectly smooth and straight) led to the series of papers and investigations outlined or described below.

Measurements of circumferentially averaged pressure:

Effect of yaw and surface roughness on fluctuating pressures at a single point on the cylinder:

Our initial measurements were made of surface pressure fluctuations using various types of condensor microphone sensors mounted inside a hollow cylinder and communicating with the surface pressure via small diameter tubes. Although this type of transducer has been found to introduce spurious high frequency fluctuations, our major interest was in the very much larger additional pressure fluctuations caused by cylinder roughness of large scale or flow induced fluctuations caused by yawing the cylinder. The result of this phase of the work led to a documentation of the pressure disturbances for yaw and surface roughness as described in the report, **Willmarth, Sharma and Inglis (1977)**, (see list in **Appendix A**).

a) Steady circumferential average of the static pressure distribution:

Following the above investigation we began the task of studying the **steady**, circumferential average of the pressure at a streamwise station on a cylinder. The investigation was conducted in the 5 X 7 foot wind tunnel of the Aerospace Engineering Department at the University of Michigan. A long, one inch diameter cylinder was instrumented to measure the instantaneous circumferential average of the static pressure at one station along the cylinder axis. The measurement was made on a one quarter inch wide band around the circumference of the cylinder.

In the case of a uniform flow past a very long cylinder the surface pressure will be equal to the free stream pressure if the cylinder axis is parallel to the flow. When the cylinder axis is inclined with respect to the flow direction a cross flow component of velocity normal to the cylinder axis causes the pressure on the windward surface to be higher than the free stream pressure on the most windward portion of the windward surface, but lower than the free stream pressure on the remaining portion of the windward surface and on the leeward surface. It turns out that the circumferential average of the pressure (integrated around the circumference of the cylinder) is less than the free stream pressure. It was found that the flow about the cylinder occurs in two regimes in which, for yaw angles less than approximately 5 degrees, the axial boundary layer is dominant and for greater yaw angles an attached vortex regime occurs on the leeward surface of the cylinder. The circumferential average of the pressure is in general a monotone decreasing function of the angle of inclination (yaw) of the cylinder axis with respect to the free stream direction. It was also found that the type of flow separation on the leeward surface of the cylinder had a considerable affect on the static pressure distribution. Under certain conditions, a considerable asymmetry of the static pressure distribution on the leeward surface was observed which was related to different configurations of shed vorticity on the leeward surface of the cylinder. A report describing these observations and measurements has been written report by Wei (1984), see the list of papers and reports in Appendix A.

b) Quasi-steady circumferential average of the static pressure distribution:

For the case of unsteady static pressure distribution at very low frequencies and for a very large scale flow inhomogeniety one can postulate the existence of a quasi-steady fluctuating pressure field about the cylinder. The results described in part a) above could then be used to determine the circumferential average of the pressure fluctuations on the cylinder. Strictly speaking one must have extremely low frequencies so that the transition between the axial boundary layer type flow and the attached vortex like flow will be complete and the true static flow field will have had time to develop.

c) Measurement of the circumferential average of the static pressure:

Owing to the uncertain validity of the above postulated quasi-steady pressure field, and for the practical cases of higher frequencies disturbances, surface roughness and small scale free-stream flow inhomogenieties a transducer was developed to directly measure the circumferential average of the instantaneous pressure on the cylinder.

Transducer:

A transducer which employs a distributed capacitance in the form of a ring or band around the cylinder was developed to measure the instantaneous circumferential average of the pressure on the cylinder. The scheme was originally developed by Sell (1937) ("Zeitschrift fur Technische Physik", **18**, Nr. 1 pp 3-10). The scheme employs a thin film of plastic (heat shrink mylar was used) which is stretched over a conductive band one quarter inch wide with numerous circumferential grooves (a very fine pitch screw thread) around the one inch diameter cylinder. Figure 1 is a sketch of the transducer. A thin film of gold is deposited on the outer surface of the mylar film by a sputtering process and forms one plate of a capacitor. The other plate is the grooved band which is supported on a rigid insulator of teflon and connected to a 200 volt supply voltage through a very high resistance of the order of 100 gigohms. When the mylar film is exposed to a change in pressure the deformation of the film into the circumferential grooves in the metal band results in a slight change in capacitance and a voltage fluctuation is produced because there is not time for the charge on the capacitor to change. The voltage fluctuation is proportional to the total change in distributed capacitance all around the cylindrical band and hence is proportional to the circumferential average of the instantaneous pressure fluctuation around the cylinder.

The frequency response of the transducer system, (the transducer was connected to a standard Bruell and Kjaier preamplifier, model 2618), was uniform from 2 to 200,000 Hz. The circumferential pressure transducer and electronic system was calibrated by exposure of the cylinder with pressure transducer to a sinusoidal sound field (a traveling sinusoidal wave) produced by a large loud speaker. The signals from the transducer were compared with those from a 1/4 inch Bruel and Kjaer microphone mounted adjacent to the cylinder. It was found that the sensitivity was approximately 1/10 of the B & K microphone and was uniform from 2 to approximately 4000 Hz. This calibration was repeated before and after each test in which the intensity of the pressure fluctuations was measured. Additional tests were made of the uniformity of the transducer response around it's circumference by attaching a fine wire to a rotating shaft and positioning the end of the wire very close to the transducer surface. This caused a pulsating signal to be produced. The spatial response around the circumference of the transducer and axially along the 1/4 inch band was found to be uniform. The response cut off rapidly at the edge of the band and by positioning the ends of two whirling wires at different locations it was established that the transducer responded to the sum of the two signals for any position of the ends of the whirling wires. It was necessary to mount the transducer on a vibration isolated segment of the cylinder because unavoidable stress waves in the metal cylinder transmitted slight motions to the metal band which produced spurious voltage fluctuations comparable to the signals produced by pressure fluctuations in the flow about the cylinder. Figure 2 is a sketch of the circumferential transducer mounted on small "O" rings to isolate it from flexural waves in the cylinder.

Fluctuating pressure measurements in a wind tunnel and in the atmosphere:

A 25 foot long vertical wind tunnel with a 1 foot octagonal cross-section which had been constructed for these and earlier tests was used to produce a high speed, low turbulence level flow. A long cylinder model fitted with the above transducer was mounted in the tunnel at yaw angles of zero, 3 and 10.6 degrees. Figure 3 is a photograph of the long cylinder (with the circumferential pressure transducer which is not visible) mounted in the vertical wind tunnel. For tests at 3 and 10.6 degrees of yaw a shorter seven foot long cylinder was used (this cylinder may be seen in Fig. 4 when mounted on the bus for atmospheric tests). For the seven foot cylinder the pressure transducer was mounted 6 feet from the nose of the cylinder. In all cases the voltage signal representing the circumferential average of the pressure fluctuations was FM recorded on analog magnetic tape for later analysis.

Measurements were also made of the instantaneous circumferentially averaged pressure when the cylinder was exposed to a flow with large scale atmospheric turbulence. The cylinder and pressure transducer were mounted on a vehicle (a recreational vehicle or bus) which was driven on an expressway at speeds of the order of 80-85 ft/sec. The cylinder and circumferential pressure transducer were suspended ahead of and on the right side of the bus using special fixtures with shock cords (which provided vibration isolation) so that the cylinder axis was parallel to the ground. All tests were made while driving in the right lane of a two lane expressway to reduce the disturbances caused by passing vehicles. Figure 4 is a photograph of the cylinder with the circumferential pressure transducer mounted on the bus along with other instruments as described below.

The turbulence in the atmosphere was of large scale (much larger than could have been obtained in a wind tunnel) and varied depending on the prevailing wind strength and direction and also was dependent on the magnitude of wake flow disturbances produced by normal traffic on the expressway (Michigan Highway M-14 between US-23 near Ann Arbor, MI. and Gottfredson road, which runs North-South near Northfield, MI.). The tests were made during the day under normal mid-afternoon or mid-morning traffic conditions. The voltage signals representing the circumferential average of the pressure fluctuations, as well as the signals from a wind direction indicator (termed a yaw vane), 3 sensor probe and propellor anemometer were all simultaneously FM recorded on analog magnetic tape for later analysis.

Root-mean-square-pressure fluctuations:

The results of the analysis of the measurements of the root-mean square circumferentially averaged fluctuating pressure are tabulated in Table I. The intensity of the circumferential average pressure fluctuations measured at zero yaw angle in the atmosphere is much greater (by approximately a factor of 2) than the intensity of pressure fluctuations measured at a single point on a 3 inch diameter cylinder at zero yaw angle. The pressure measured at a point is described in the paper by Willmarth and Yang (1970), JFM, who found a value of the ratio of rms pressure at a point on a cylinder to free stream dynamic pressure of $p'/q_\infty \approx 0.006$. It was found that at 3^0 angle of yaw, the rms circumferentially averaged pressure fluctuations were 17% larger than at zero yaw, but at a 10.6^0 degree yaw angle the same rms pressure fluctuations had decreased to 20% of the rms value at zero yaw. These measurements indicate that the magnitude of the circumferentially averaged pressure fluctuations produced by turbulence in the boundary layer is much larger than the local component measured at a point. The circumferential average of the pressure must include a wake like component correlated all around the cylinder and a component produced by aerodynamic interaction of turbulence with the cylinder surface.

In Table I, for the clear air case in which no vehicles were within a quarter mile of the bus as it traveled on the highway, the naturally occurring turbulence resulted in a root-mean-square intensity of the circumferential averaged pressure fluctuations 1.79 times as large as measured in the wind tunnel at zero yaw angle. In the wake of a small truck, the intensity was 3.24 times as large as in the wind tunnel at zero yaw and in a large truck wake (large tractor-trailer combination) only 100-200 feet behind the vehicle the intensity was a factor of 6.53 times larger than at zero yaw in the wind tunnel. We therefore conclude that free stream turbulence and/or cross-stream motion of the cylinder relative to the air can cause large contributions to the circumferential average pressure fluctuations. It should also be noted that Batchelor (1951) gives a value for the rms pressure fluctuations in isotropic turbulence of $p'/q_{turb} \approx 1.16$, which value is based on measurements of Proudman (1951). This is much less than the measured circumferential average of the pressure fluctuations which have a value (based on measurements of the turbulent velocity fluctuations to be described later) of, $p'/q_{turb} \approx 6.93$ in clear air, again indicating that interaction with the surface of the cylinder gives rise to increased intensity of the pressure fluctuations on the surface of the cylinder.

Measurements of the power spectra of the pressure fluctuations:

A digital computer fitted with an analog to digital converter was used to convert the analog pressure fluctuation data to digital form so that the power spectra could be found using the fast Fourier transform algorithim. Power spectra measurements revealed that the primary difference in the spectra of the circumferentially averaged pressure fluctuations in the wind tunnel and in the atmospheric was the existence of very low frequency, large amplitude pressure fluctuations in the atmosphere which were not present in the wind tunnel. Figure 5 is a typical plot of the power spectra measured in the wind tunnel and in the atmosphere in clear air which illustrates this finding.

Flow velocity components normal to the cylinder axis (cross flow) are important in producing the circumferentially averaged pressure fluctuations. It was observed that the amplitude of the pressure fluctuations on the cylinder were large even when the vehicle was stationary and the slight (of the order of 7-10 ft/sec) prevailing wind was at a large angle (of the order of 90^0) to the axis of the cylinder. It appears that with the small wind tunnel cross-sectional dimensions (of the order of 12 inches) no turbulent eddies larger than the cross-sectional dimensions of the wind tunnel can be accommodated in the flow about the cylinder, thus preventing the large scale cross-flow that can occur in the atmosphere. In the atmosphere the scale of the turbulence is limited only by the proximity of the ground which is approximately 3.5 feet below the cylinder axis and the front of the bus which is 4-5 feet behind and to the side of the cylinder axis.

Measurements of the velocity field near the cylinder:

The above results strongly suggest that the large scale turbulent flow in the free stream about the cylinder is responsible for a very great increase in the fluctuating circumferentially averaged pressure on the cylinder when exposed to turbulent flow in the atmosphere. The question of the relationship between the turbulent flow fluctuations in the free stream and the pressure fluctuations measured on the cylinder was studied with the aid of measurements of the velocity field in the flow near the cylinder and the pressure developed on the cylinder.

A three-component hot-wire probe (Model 1298 manufactured by TSI) was purchased and calibrated in a wind tunnel for use in the measurement of the turbulent velocity fluctuations near the pressure measurement station on the cylinder. The probe calibration data showed that for the present purpose a sufficiently accurate representation of the response of each hot-wire sensor (with aspect ratio 333) could be obtained by simply assuming that the sensor cooling velocity is the velocity normal to the axis of the wire (the cosine law). In addition to the hot-wire, a Gill propellor anemometer and a relatively simple wind direction indicating device (termed a yaw vane) were used to determine the mean flow direction and velocity relative to the bus. The wind direction indicator (yaw vane) was constructed using a potentiometer to which a simple balsa wood wind direction vane with balancing weight was attached. The three sensor hot-wire probe was fastened to the cylinder behind the pressure sensor with the probe parallel to the cylinder axis and the three hot-wire sensors 3.75 inches directly above the pressure measuring station. Figure 4 is a photograph of the experimental arrangement of the above measuring devices as mounted on the bus for tests in the atmosphere.

The bus was driven on the highway at speeds between 70 and 85 ft/sec. and the signals from all the above sensors were recorded on FM analog magnetic tape for later analysis by a digital computer. The method of analysis to determine the velocity components from the recorded signals was dependent on calibration of the probe in a small wind tunnel. The calibration and data reduction procedure are described in a report **Willmarth, Wei and Madnia (1984)** as listed in item 6) in **Appendix A.**

Relationship between pressure fluctuations and measured flow fluctuations:

The remainder of the work on this contract was directed towards documenting the cause and nature of the circumferentially averaged pressure fluctuations. To accomplish this we concentrated on the relationship between the flow fluctuations measured 3.5 inches radially upward (above) the point on the cylinder where the circumferentially averaged pressure fluctuations were measured. We first studied various correlation coefficients between the circumferentially averaged pressure fluctuations and the velocity fluctuations. Table II contains typical results of the pressure velocity fluctuation correlation measurements in atmosphere for various free stream turbulence intensities. In all cases, the pressure fluctuations are negatively correlated with the axial component of the free stream velocity fluctuations measured 3.5 inches above the pressure transducer. This result is in accord with a quasi steady Bernoulli's law for potential flow. We note that the location of the hot-wire measurement station is well outside the average location of the outer edge of the boundary layer on the cylinder.

We also observe that the pressure is negatively correlated with the horizontal cross flow velocity fluctuations measured 3.5 inches above the cylinder. From symmetry considerations, the spanwise or yawing velocity fluctuations should not be correlated with the average pressure fluctuations around the cylinder if the cylinder axis is at zero angle of yaw with respect to the flow. Since the wind on the highway tests was not parallel to the path of the vehicle a non zero correlation was measured because the mean cross-flow velocity was not zero (thus giving rise to an asymmetric flow field). The correlation of the vertical component of the cross flow velocity with the pressure fluctuations is 0.263 for clear air, but is nearly zero for the two cases of larger free stream turbulence. Further measurements will be required to fully understand the present results. At the present time we do not understand the behavior of the pv correlation.

Models for the pressure fluctuations:

Various simple models for the instantaneous magnitude of the circumferential average of the instantaneous pressure fluctuations as a function of the measured instantaneous velocity fluctuations were examined. A simple equation,

$$p - < p > = k\,(u^2 - < u >^2)$$

was used to model the pressure fluctuations. As discussed below this model was quite good. For this model the value of the constant, k, in clear air was determined on the basis that the mean-square-difference between the actual and the modeled pressure fluctuations (i.e. the variance) should be a minimum. From this minimum condition and measurements of the correlation between the pressure and the velocity squared (determined by digital computation) the value of the constant was found to be, $k = -0.203$. Using this value, the traces of the actual and the modeled pressure fluctuation were plotted and are displayed in Fig. 6. It can be observed that the agreement between the actual and modeled pressure fluctuations is relatively good. In addition to the traces shown in Fig. 6, the correlation coefficient between the modeled and actual pressure fluctuations was computed and found to be 0.661. This value is a reasonably high correlation, but clearly the pressure is not entirely caused by streamwise velocity fluctuations. A similar procedure was employed for the measurements in the truck wake. It was found that the model worked almost as well as for clear air. The constant, k, was determined to be, $k = -0.221$. The value of the correlation coefficient between the actual pressure and the modeled pressure was 0.510.

In an attempt to obtain a better model, the formula

$$p - < p > = k\,(u^2 - < u >^2) + b(\,v_c - < v_c >\,)$$

where $v_c = [\,(\,v - < v >)^2 + (\,w - < w >\,)^2\,]^{1/2}$ was used as a model and the constants, k & b, were determined (for the clear air case) by minimizing the variance of the actual and modeled pressure. For this determination it was found that the correlation coefficient between the modeled and actual pressure fluctuations, in clear air, was 0.602 which is slightly less than the simple model with only the term u^2.

Relation between the pressure and convected disturbances in the free stream:

In an attempt to learn more about the origin of the pressure fluctuations, the correlation between various velocity component fluctuations, the pressure and the signal from the yaw vane downstream of the pressure transducer were studied. The largest magnitude correlation coefficient was found to be that between pressure and square of the streamwise velocity component, in agreement with the model results given above. The correlation between pressure and the cross flow velocity component in the upwards direction (the component, v) is 0.263. This is thought to be caused by an aerodynamic interaction between the flow and the cylinder. The correlation with the cross flow component, w, is -0.322, in clear air. We believe that this correlation is caused by asymmetry of the flow since the average cross flow velocity component, w (i.e. the average yaw angle) was not zero.

In the case of the truck wake, a rather striking large correlation coefficient of -0.525 was measured, see Table I. We examined traces of these signals and the result clearly shows this correlation. These traces are shown in Fig. 7. The cause of this large correlation, for this case, appears to be the presence of a prevailing mean cross flow from the wind, which is modulated by the velocity fluctuations associated with the large scale vorticity in the wake of the truck.

Further studies of the relation between the pressure fluctuations on the cylinder and the velocity fluctuation component, w, were made. The pressure, yaw vane signal and velocity signals (measured in clear air) were digitally low-pass filtered at a 55 Hz roll-off frequency. We used a digital smoothing algorithim. This corresponds to removing signals with a spatial scale less than about a foot (assuming Taylor's convection concept is valid). The correlation coefficient of the pressure and the yaw vane signal (the yaw vane is downstream of the pressure transducer) was measured and found to be 0.236. However, with time delay of the pressure signal a maximum of the space -time correlation coefficient was found. This maximum was 0.451 at a time delay of 0.04 seconds. The space-time correlation measurements are shown in Fig. 8. Also shown in Fig. 8 is the space-time correlation between the yaw angle measured by the hot-wire at the hot-wire station and the yaw vane signal. This shows a maximum correlation coefficient of, 0.760, at a time delay of the hot-wire signal of .04 seconds. Since the free stream speed was 72.6 ft/sec the distance computed from the time delay and this speed is, 2.9 ft. This is in good agreement with the actual streamwise distance between the yaw vane fin and the hot-wire/pressure transducer location. It is concluded that large scale turbulence in the atmosphere is indeed responsible for a very significant contribution to the low frequency, large scale circumferentially averaged pressure fluctuations on a cylinder.

TABLE I

MAGNITUDE OF CIRCUMFERENTIAL RMS PRESSURE FOR VARIOUS CONDITIONS

WIND TUNNEL:

YAW ANGLE DEGREES	RMS PRESSURE p'/q	TURBULENCE LEVEL	COMMENTS
0	0.0179	<0.5%	LARGE WIND TUNNEL
3	0.021	<0.5%	SOUND FIELD @ 5-20 HZ
10.6	0.0149	<0.5%	BIG YAW LESS THAN ABOVE!

ATMOSPHERE:

YAW ANGLE DEGREES	RMS PRESSURE p'/q	TURBULENCE LEVEL	COMMENTS
0	0.0275*	6.30%	CLEAR AIR, WIND < 5 MPH
0	0.0586	19.4%	SMALL TRUCK WAKE
0	0.117	32.5%	BIG TRUCK WAKE

*BATCHELOR AND PROUDMAN GIVE: $P' = 1.16\, q'_{turb.}$, (IDEAL TRANSDUCER)

THIS MEASUREMENT GIVES: $P' = 6.93\, q'_{turb.}$

CONCLUSION: <u>FLOW INTERACTION WITH CYLINDER IS DOMINANT</u>

TABLE II

CORRELATIONS OF PRESSURE AND VELOCITY COMPONENTS

	CLEAR AIR	TRUCK WAKE	BIG TRUCK WAKE
TURBULENCE LEVEL	6.30%	19.35%	32.50%
CORRELATION:			
$\overline{PU}/P'U'$*	-0.576	-0.510	-0.094
$\overline{PW}/P'W'$	-0.332	-0.525	-0.321
$\overline{PV}/P'V'$	0.263	0.037	-0.030

* ( )' INDICATES RMS VALUE

APPENDIX A:

Chronological List of Papers and Reports:

1) Willmarth, W. W. Sharma, L.K. and Inglis, S. (1977) "The Effect of Cross Flow and Isolated Roughness Elements on the Boundary Layer and Wall Pressure Fluctuations on Circular Cylinders." Department of Aerospace Engineering, University of Michigan, Report 014439-01. January 1977. (Copy Enclosed).

2) Willmarth, W. W. and Bogar, T. J. (1977) "Survey and New Measurements of turbulent structure near the wall." Physics of Fluids, **20**, No. 10 Pt. 11 October 1977. (Reprint Enclosed).

3) Kastrinakis, E. G., Eckelmann, H. and Willmarth, W. W. (1979) "Influence of the flow velocity on a Kovasznay type vorticity probe." Rev. Sci. Instrum. **50** (6), June 1979. (Reprint Enclosed).

4) Wei, T. and Willmarth, W. W. (1983) "Static pressure distribution on long cylinders as a function of angle of yaw and Reynolds number." Department of Aerospace Engineering, University of Michigan, Report 014439-02. July 1983. (Copy Enclosed).

5) Willmarth, W. W. and Sharma, L. (1984) "Study of turbulent structure with hot wires smaller than the viscous length", J. Fluid Mech, **142**, pp 121-149. (Reprint enclosed).

6) Willmarth, W. W., Wei, T. and Madnia, K. (1984) "Time Resolved Measurements of Large Amplitude Velocity Fluctuations with a Three-Sensor Hot-Wire Probe", Report 014439-03 Department of Aerospace Engineering Univ. of Michigan, November 1984. (Copy enclosed).

7) Willmarth, W. W. (1985) "Geometric interpretation the possible velocity vectors obtained with multiple-sensor probes." Physics of Fluids, **28** (2), February 1985. (Reprint Enclosed).

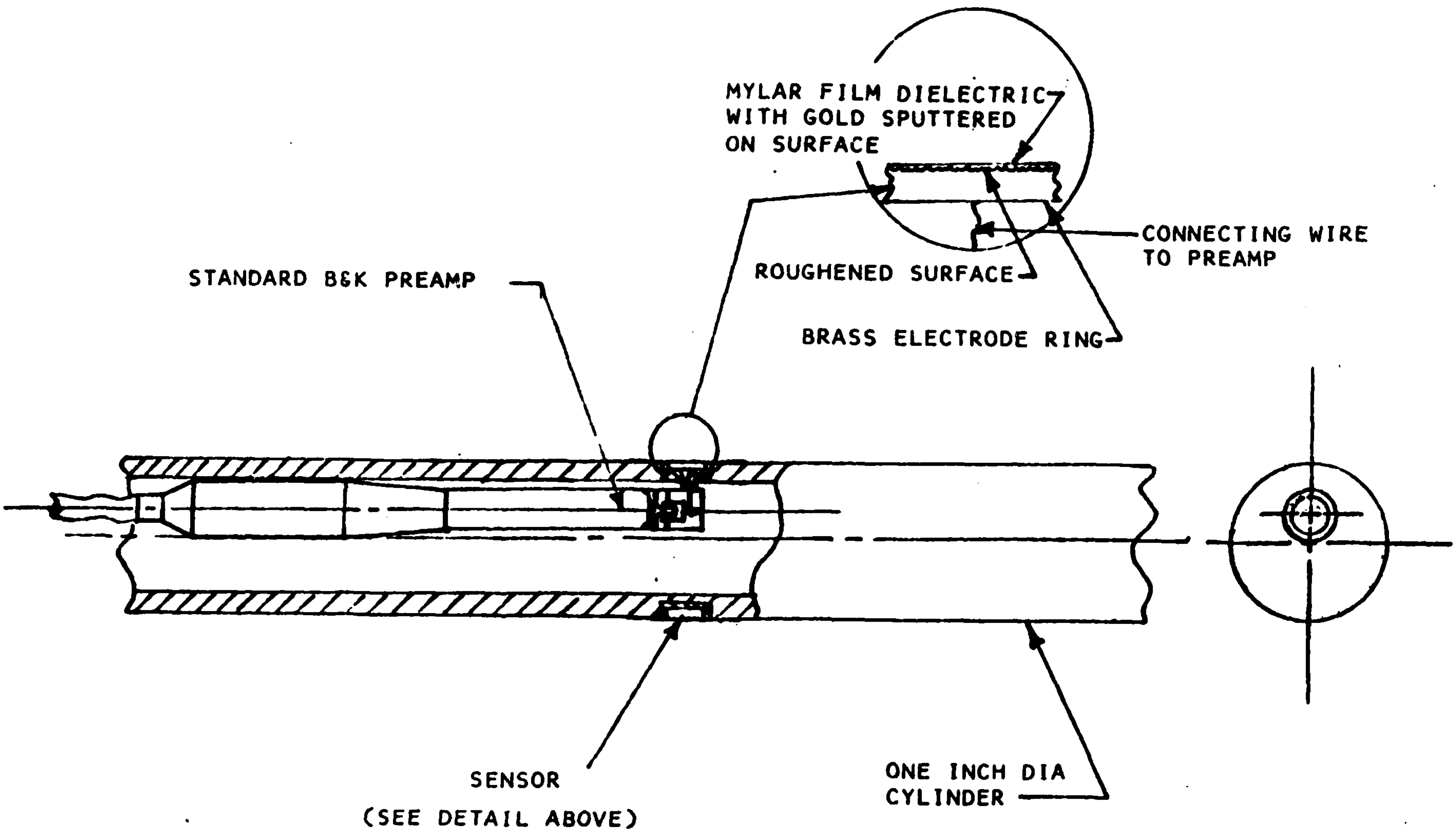
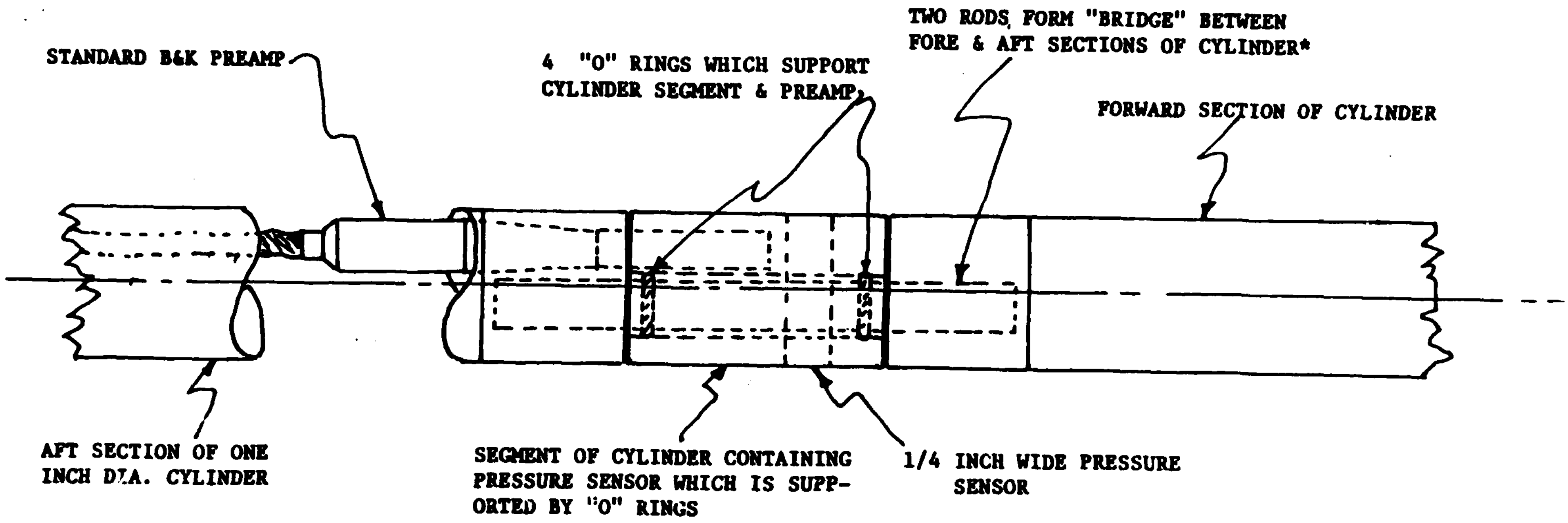


FIGURE 1 CIRCUMFERENTIAL PRESSURE TRANSDUCER. CYLINDRICAL SENSOR IS 0.25 IN. WIDE



* THE RODS JOIN THE FORE AND AFT SECTIONS OF THE CYLINDER AND HAVE GROOVES CUT IN THE SURFACE TO POSITION THE "O" RINGS WHICH SUPPORT THE CYLINDER SEGMENT WHICH CONTAINS THE PRESSURE SENSOR & PREAMP

FIGURE 2 DIAGRAM OF VIBRATION ISOLATED PRESSURE SENSOR

FIGURE 3 CYLINDER MODEL WITH CIRCUMFERENTIAL PRESSURE TRANSDUCER IN VERTICAL WIND TUNNEL.

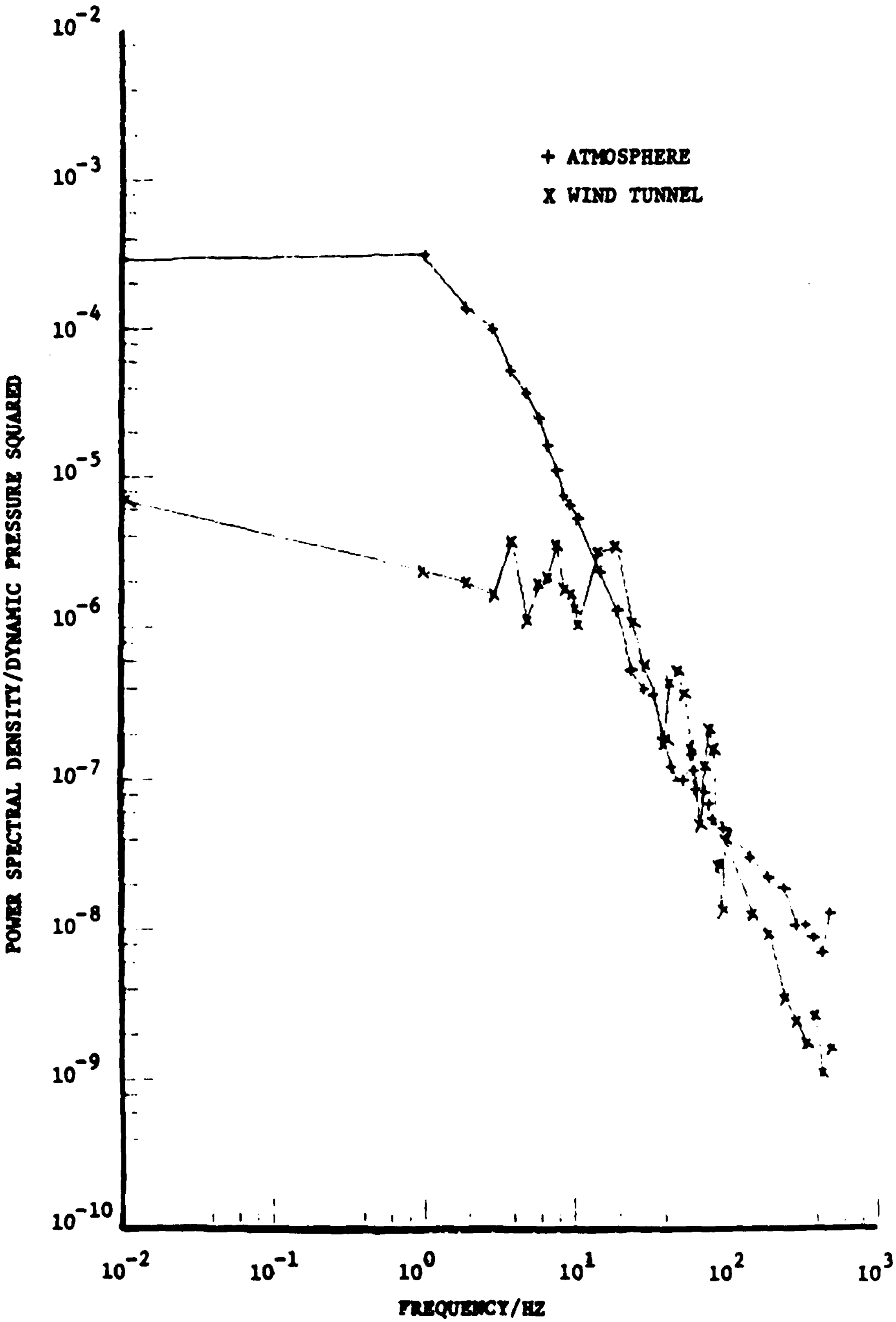


FIGURE 5 POWER SPECTRA OF THE CIRCUMFERENTIAL INTEGRAL OF THE PRESSURE FLUCTUATIONS ON A CYLINDER IN A WIND TUNNEL AND IN THE ATMOSPHERE.

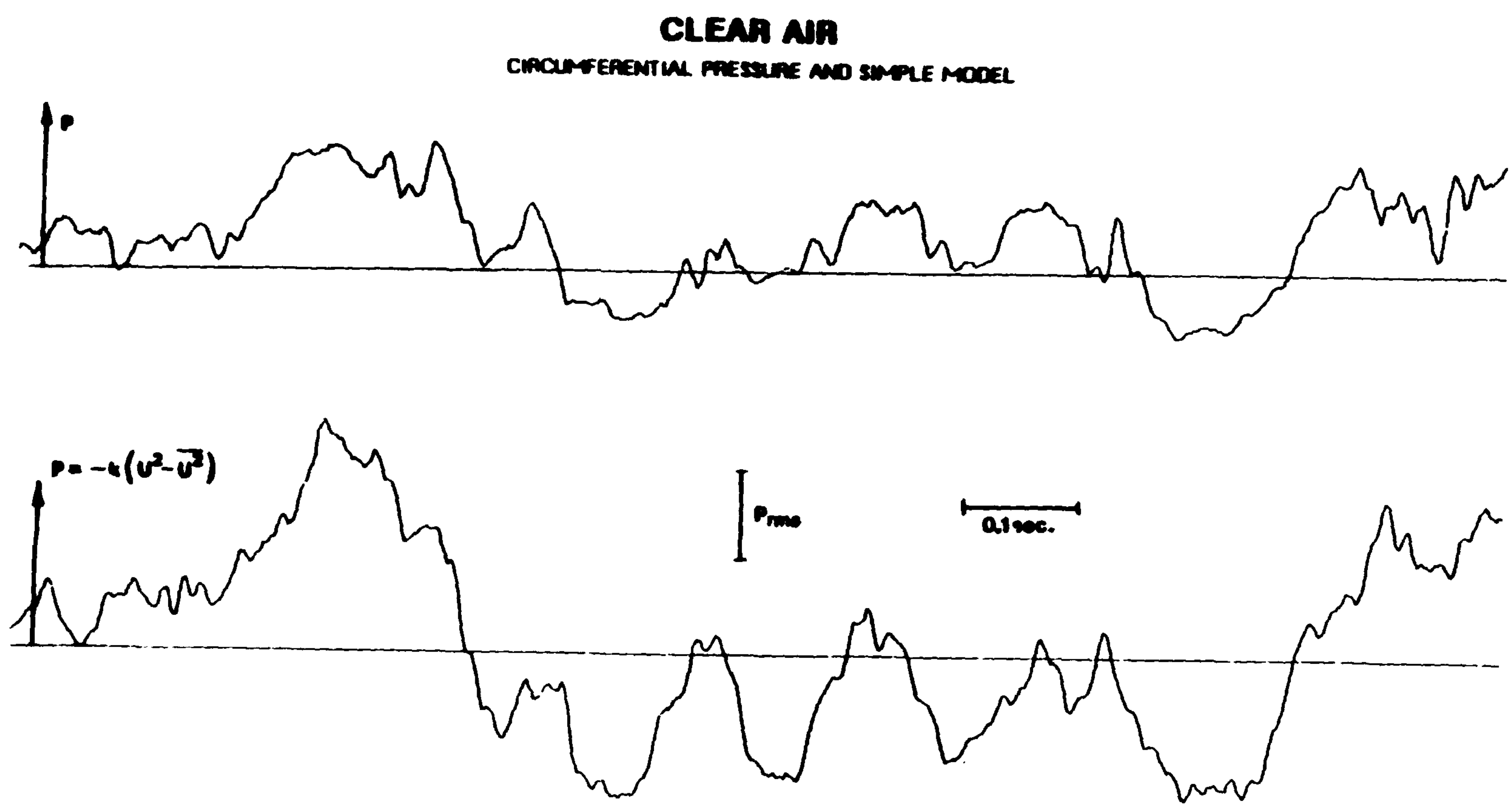


FIGURE 6 TRACES OF THE ACTUAL AND MODELED INSTANTANEOUS VALUES OF THE CIRCUMFERENTIAL AVERAGE OF THE PRESSURE ON A CYLINDER IN CLEAR AIR.

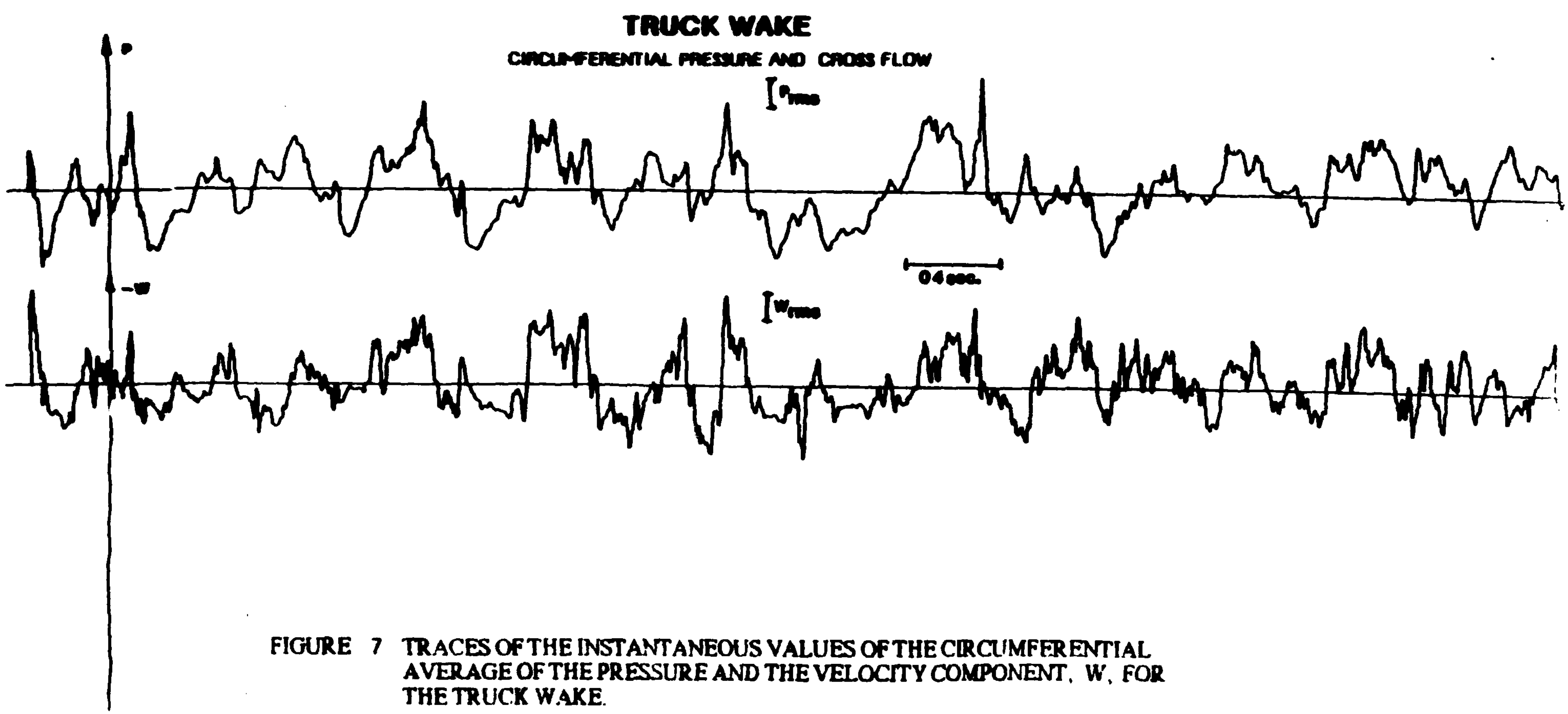


FIGURE 7 TRACES OF THE INSTANTANEOUS VALUES OF THE CIRCUMFERENTIAL AVERAGE OF THE PRESSURE AND THE VELOCITY COMPONENT, W, FOR THE TRUCK WAKE.

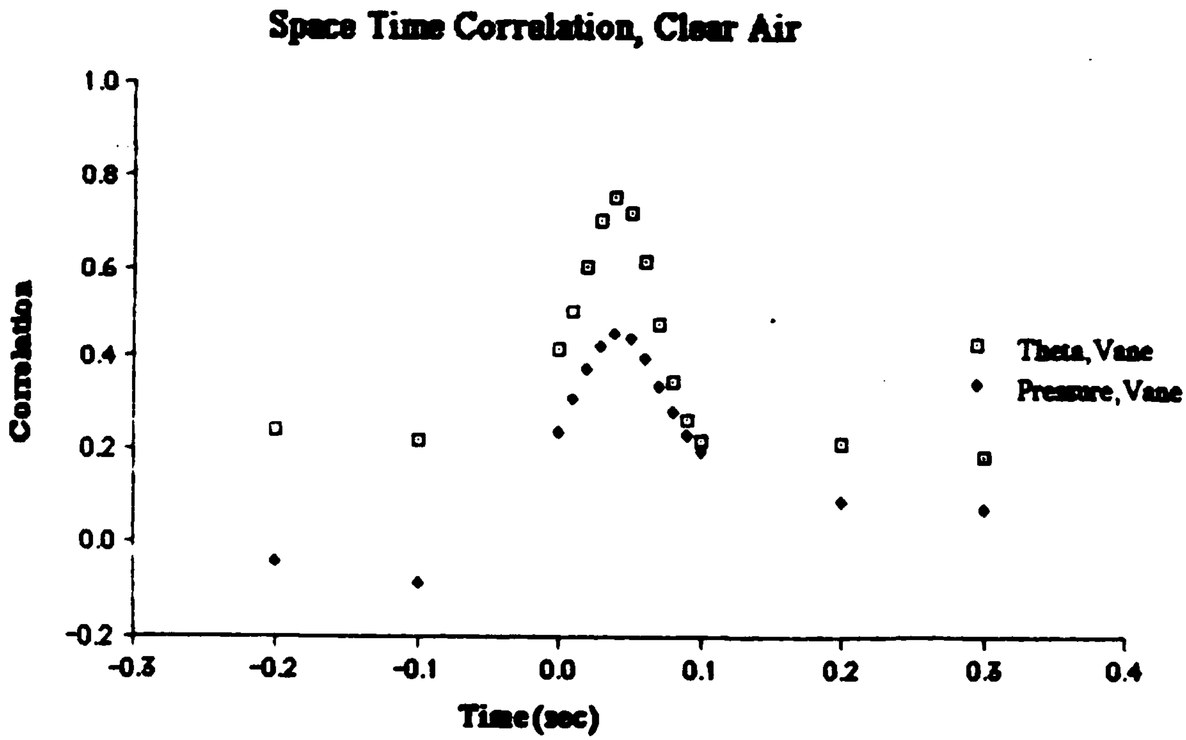


FIGURE 8 SPACE-TIME CORRELATION OF THE CIRCUMFERENTIAL AVERAGE OF THE PRESSURE FLUCTUATIONS AND THE YAW VANE SIGNAL IN CLEAR AIR.

IN ADDITION THE SPACE TIME CORRELATION OF THE FLOW INCLINATION NEAR THE MEASUREMENT STATION (THETA) AND THE YAW VANE SIGNAL IN CLEAR AIR ARE ALSO SHOWN.

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